

*Future physics Opportunities in Beam Energy Scan at RHIC*

# Study the QCD Phase Structure in High-Energy Nuclear Collisions

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# Outline

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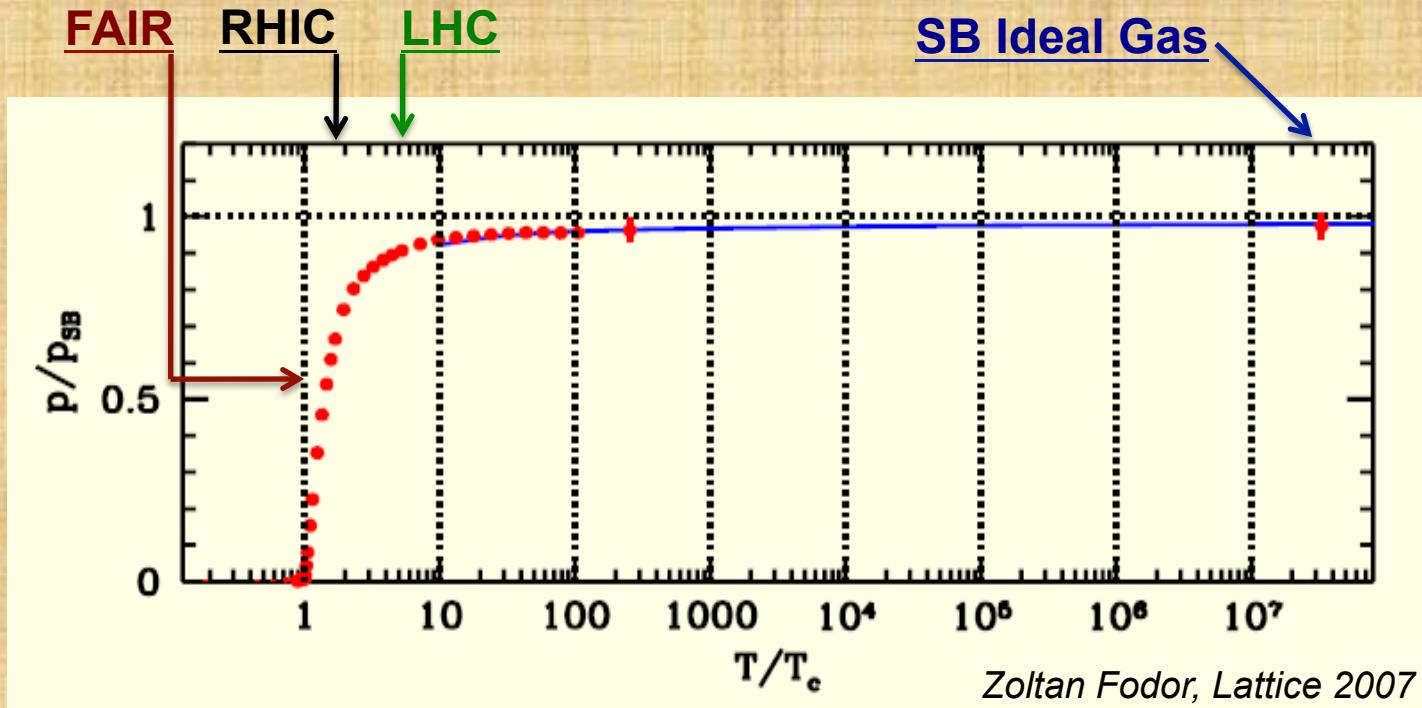
## (1) Introduction

## (2) Recent Results from BES-I

- i. Collectivity; ii. Criticality; iii. Chirality

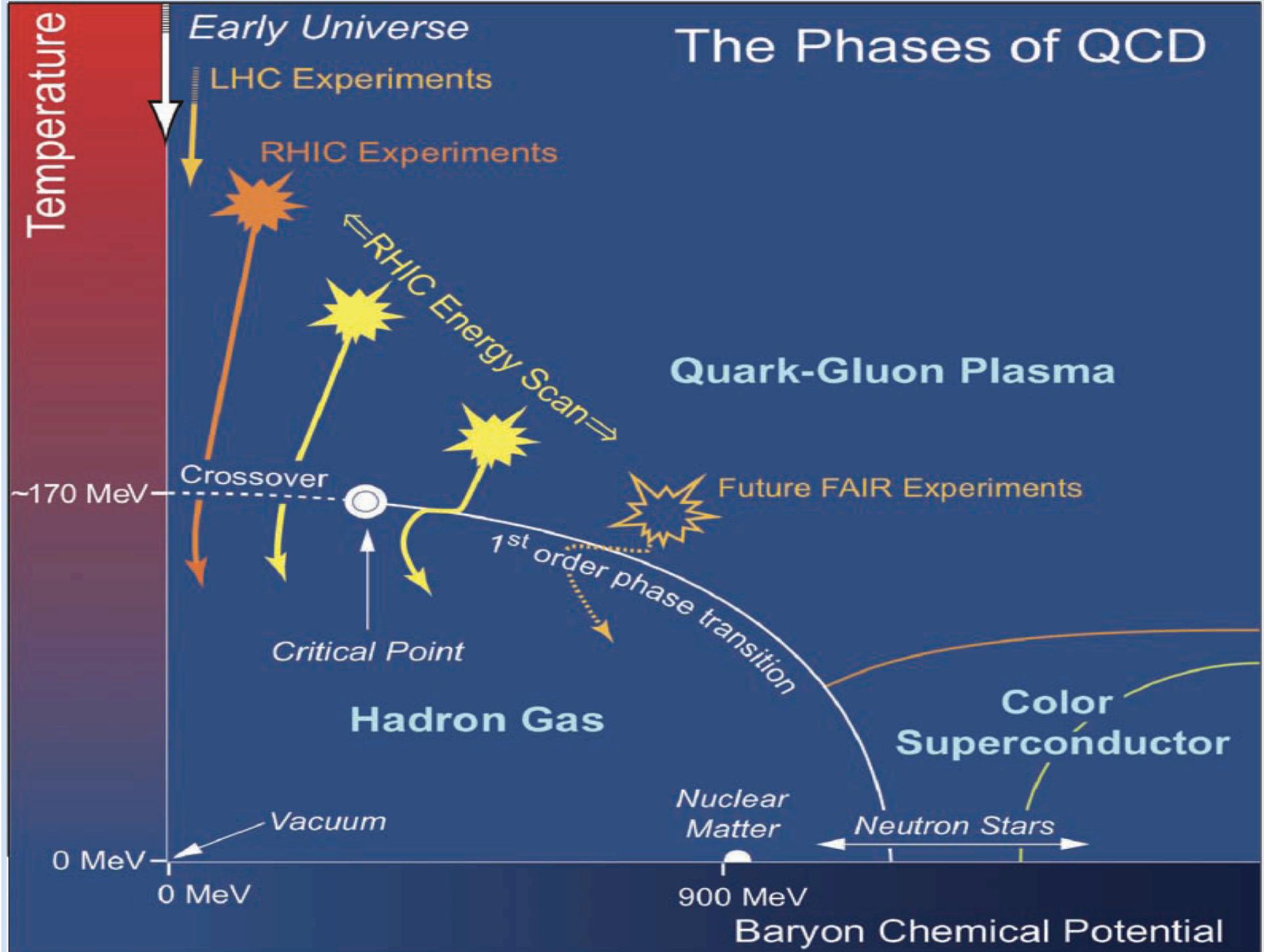
## (3) Physics Program in BES-II

# QCD Thermodynamics



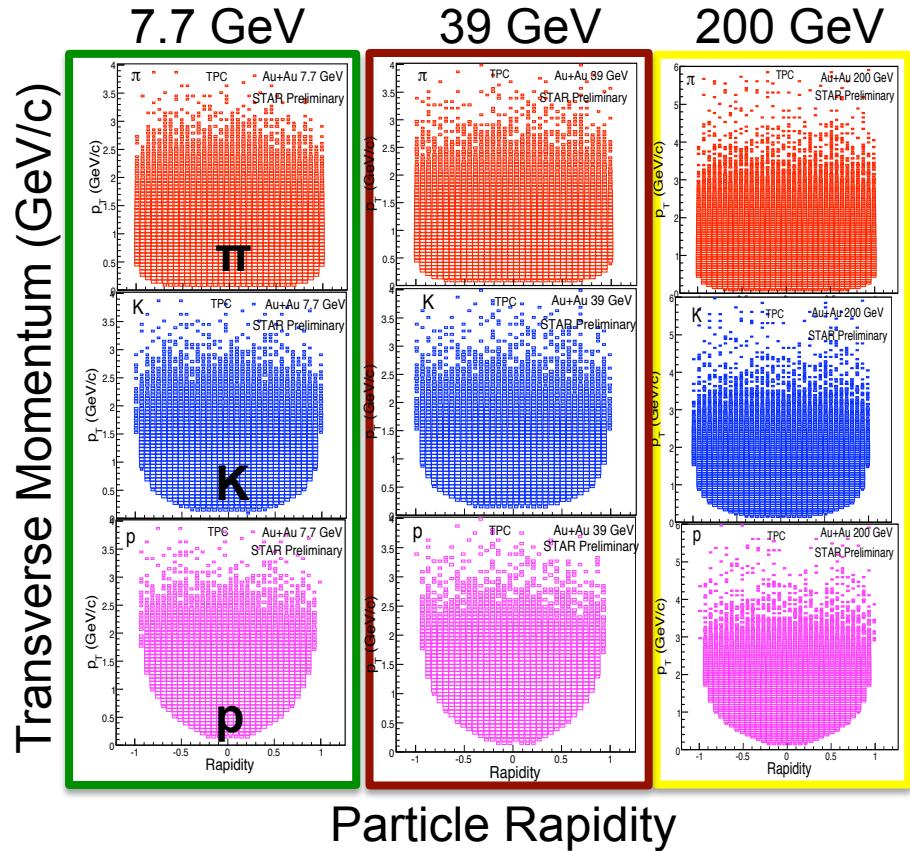
- 1) At  $\mu_B = 0$ : cross over transition,  $140 < T_c < 160 \text{ MeV}$
- 2)  $T_{ini}(\text{LHC}) \sim 2\text{-}3 * T_{ini}(\text{RHIC})$
- 3) Thermalized, evolutions are similar for RHIC and LHC
- 4) RHIC BES and FAIR: large  $\mu_B$ , rapid changes occurs

# The Phases of QCD



# Data Sets at STAR

$\sqrt{s_{NN}}$ (GeV)	Events ( $10^6$ )	Year	* $\mu_B$ (MeV)	* $T_{CH}$ (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	316	152
7.7	4	2010	422	140



- 1) Largest data sets versus collision energy: **Many thanks to RHIC operation!**
- 2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Important for fluctuation analysis!

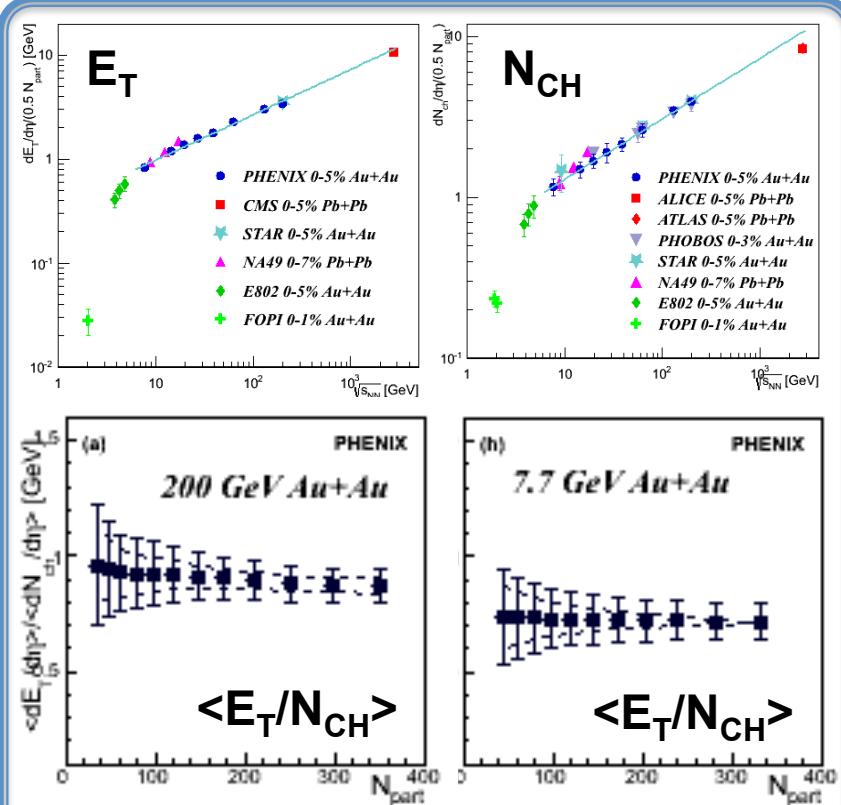
\*( $\mu_B$ ,  $T_{CH}$ ): J. Cleymans et al., PRC 73, 034905 (2006)  
Talk by J. Thäder, at QM2015



# PHENIX Results on $E_T$ and $N_{CH}$



$\sqrt{s_{NN}}$ (GeV)	System	Year	$N_{events}$
62.4	Au+Au	2004	20 M
62.4	Au+Au	2010	12 M
39	Au+Au	2010	132 M
27	Au+Au	2011	24.5 M
19.6	Au+Au	2011	6.3 M
14.5	Au+Au	2014	6.8 M
7.7	Au+Au	2010	803 k



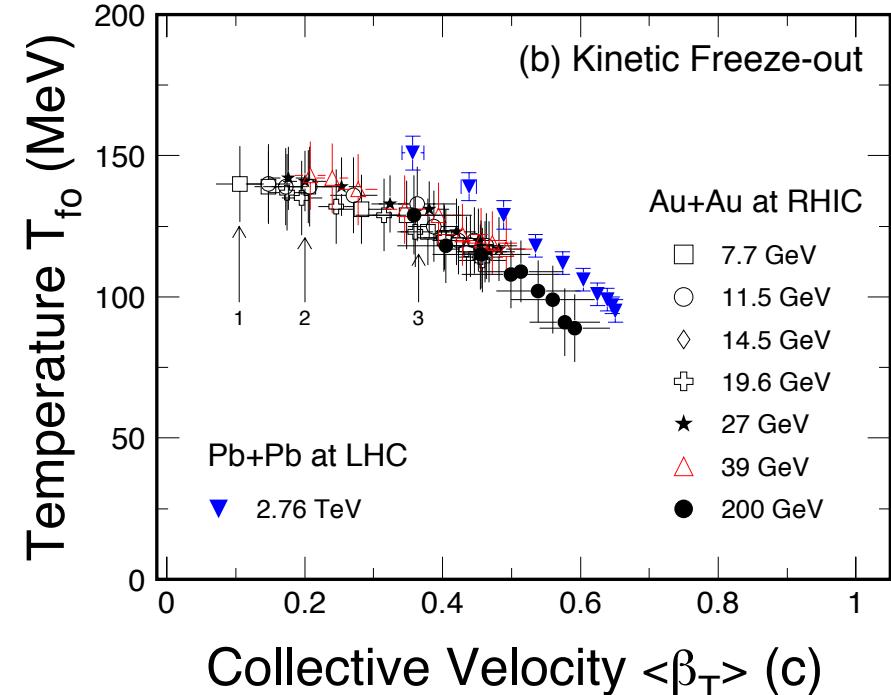
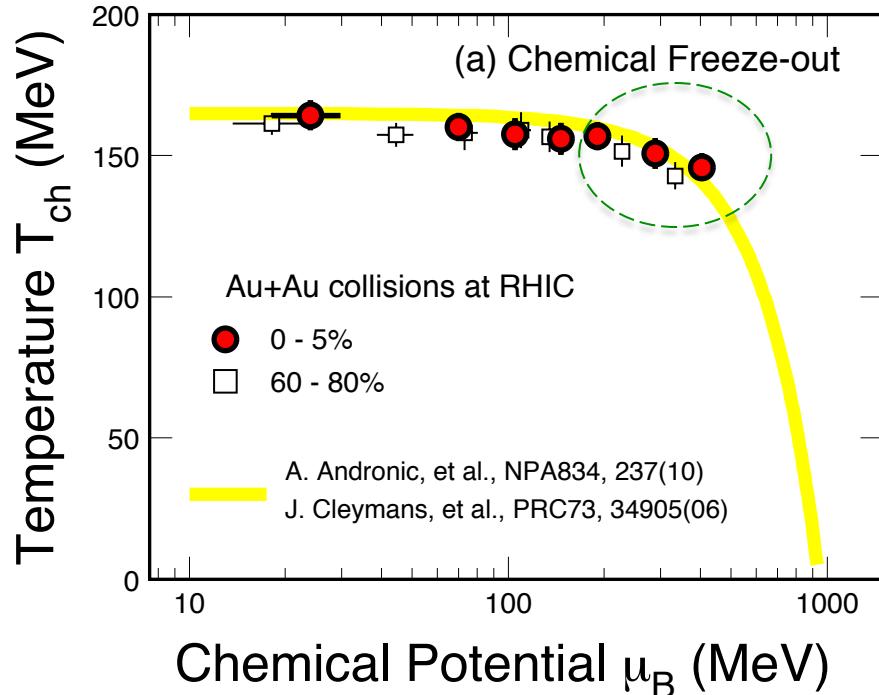
- A comprehensive survey of  $E_T$  and  $N_{ch}$  production has been recently submitted to the arXiv: arXiv: 1509.06727

- Talk by J. Mitchell at QM2015

- 1) Averaged  $E_T$  and  $N_{CH}$  increase vs. collision energy
  - 2)  $E_T$  per charged particle is flat vs. centrality and weak energy dependence
- 3) Energy density vs. energy:**

$$\varepsilon_{BJ} \cdot \tau \propto \left( \sqrt{s_{NN}} \right)^{0.38}$$

# Bulk Properties at Freeze-out



## **Chemical Freeze-out: (GCE)**

- Weak temperature dependence
- Centrality dependence  $\mu_B$ !
- Lattice prediction on CP around  $\mu_B \sim 300 - 400$  MeV

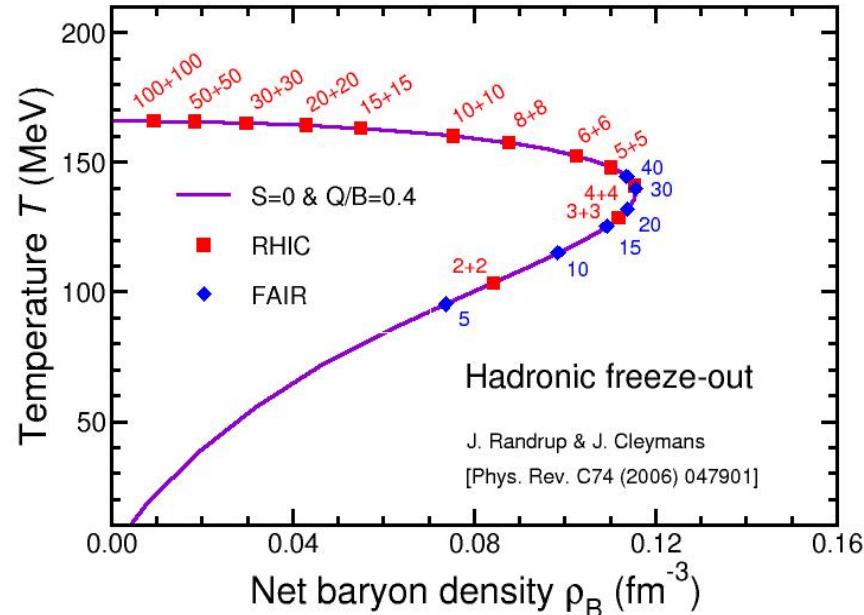
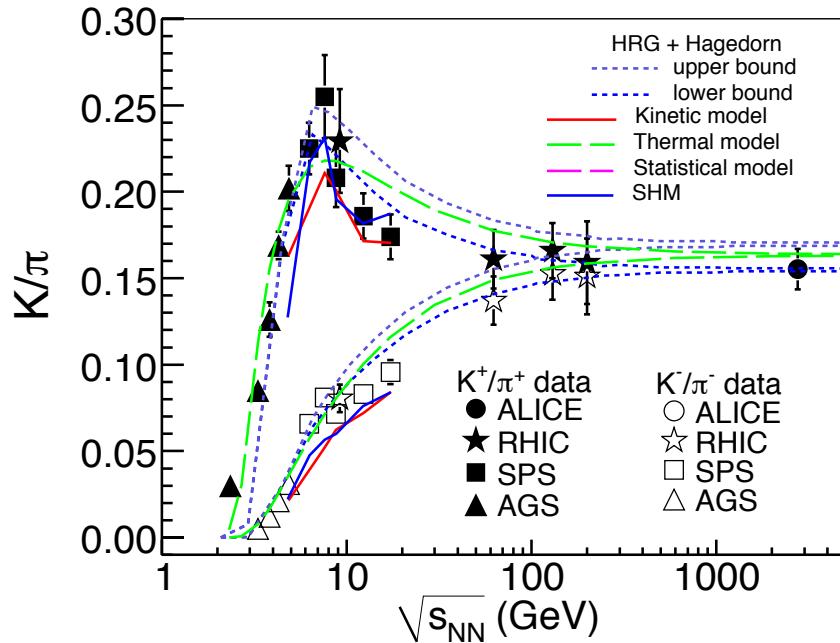
## **Kinetic Freeze-out:**

- Central collisions => lower value of  $T_{fo}$  and larger collectivity  $\beta_T$
- Stronger collectivity at higher energy, even for peripheral collisions

ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(2013).

STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)

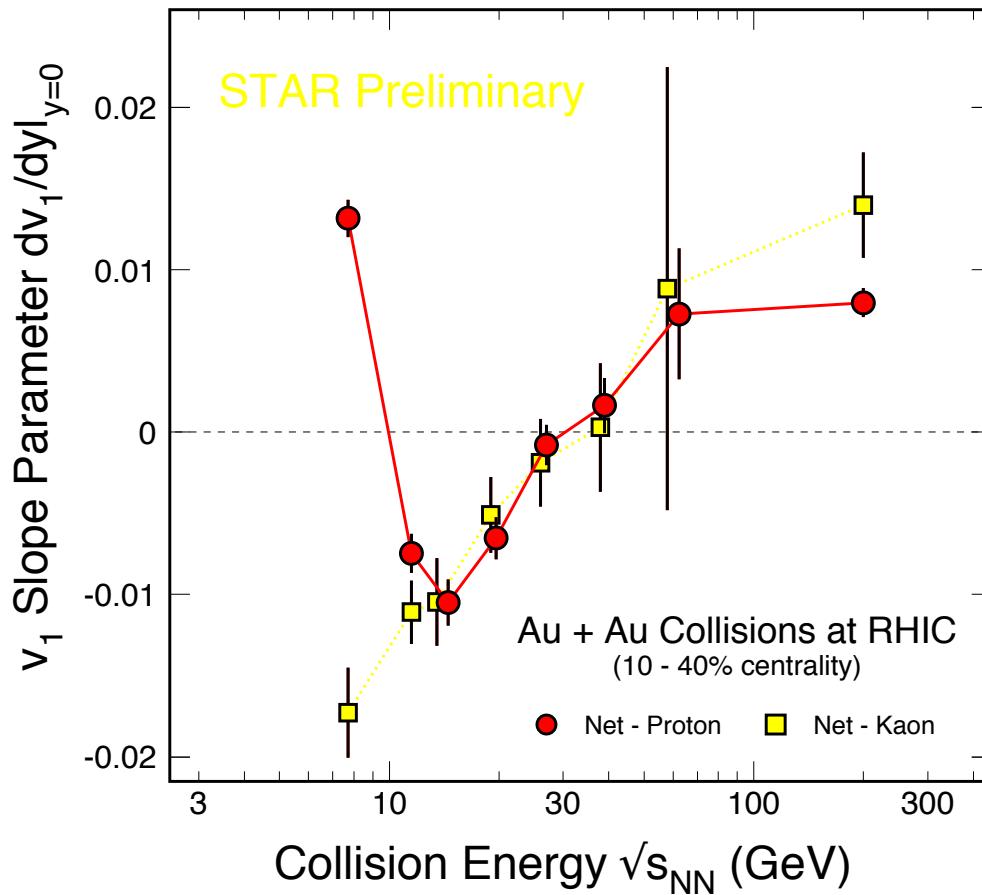
# $K^+/\pi$ Ratios and Baryon Density



- 1) In heavy ion collisions  $K^+/\pi$  ratio peaks at  $\sqrt{s_{NN}} \sim 8$  GeV,  $K^-/\pi^-$  ratio is a smooth and merges with  $K^+/\pi$  at higher collision energy
- 2) Model: Baryon density reaches a maximum at  $\sqrt{s_{NN}} \sim 8$  GeV
- 3) At  $\sqrt{s_{NN}} > 8$  GeV, pair production becomes important

L. Kumar, et al. 1304.2969

# Directed Flow $v_1$ Results

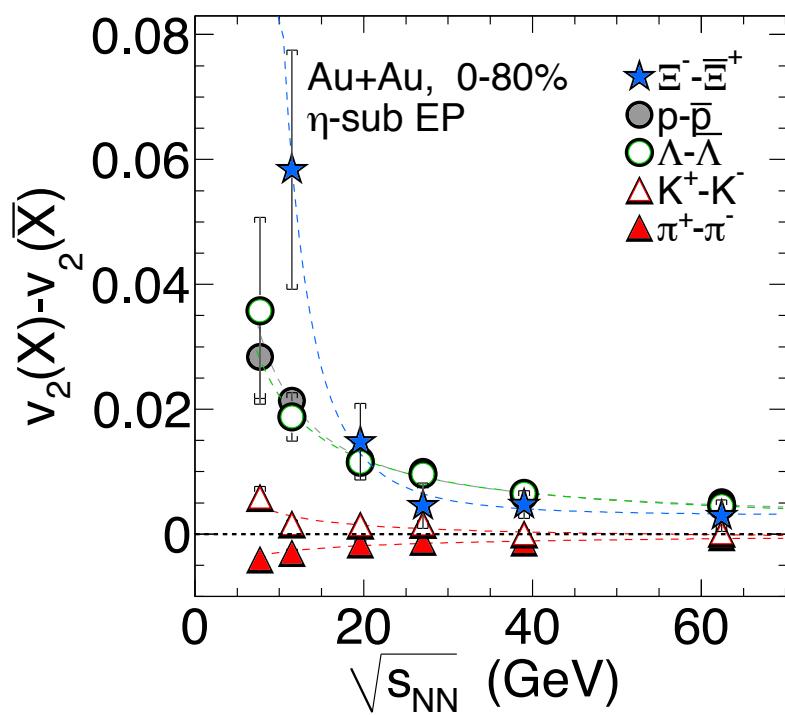
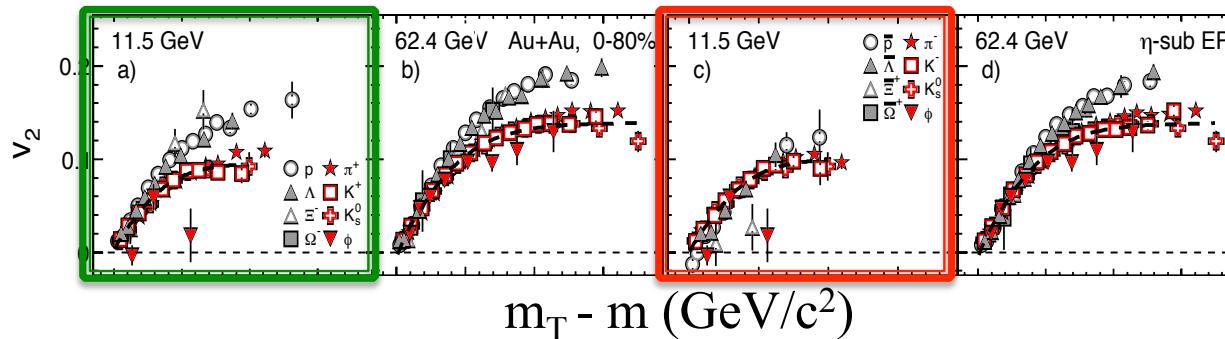


- 1) Mid-rapidity net-proton  $dv_1/dy$  published in 2014 by STAR, except the point at 14.5 GeV
- 2) Minimum at  $\sqrt{s_{NN}} = 14.5$  GeV for net-proton, but net-Kaon data continue decreasing as energy decreases
- 3) At low energy, or in the region where the net-baryon density is large, repulsive force is expected,  $v_1$  slope is large and positive!

M. Isse, A. Onishi et al, PRC72, 064908(05)

STAR: PRL112, 162301(2014)  
 Talk by P. Shanmuganathan at QM2015

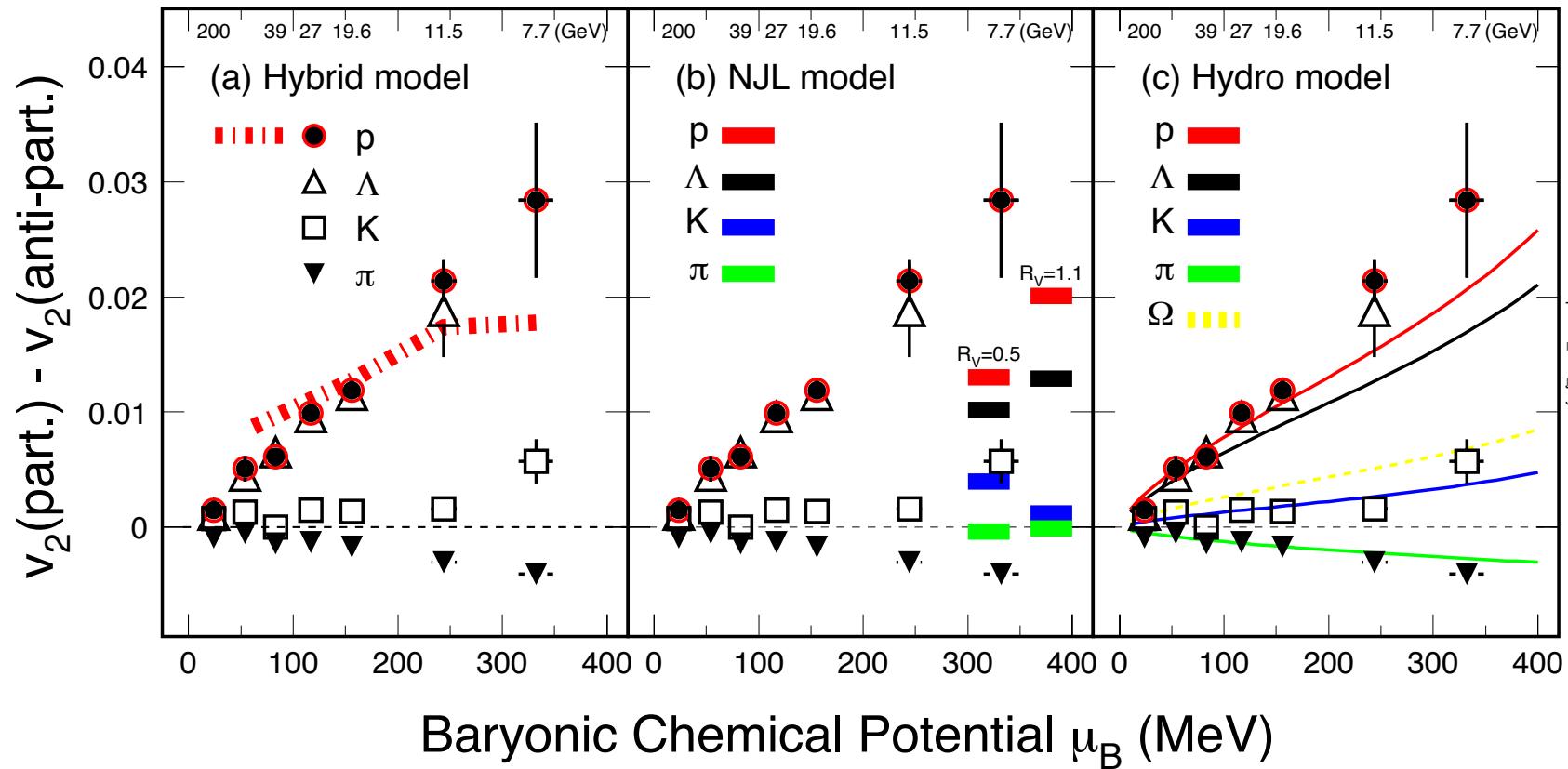
# Collectivity $v_2$ Measurements



STAR: PR110 (2013) 142301

- 1) Number of constituent quark (NCQ) **scaling** in  $v_2$   
**=> partonic collectivity**  
**=> deconfinement** in high-energy nuclear collisions
  
- 2) At  $\sqrt{s_{NN}} < 11.5$  GeV, the universal NCQ **scaling** in  $v_2$  **is broken**, consistent with hadronic interactions becoming dominant

# BES $v_2$ and Model Comparison

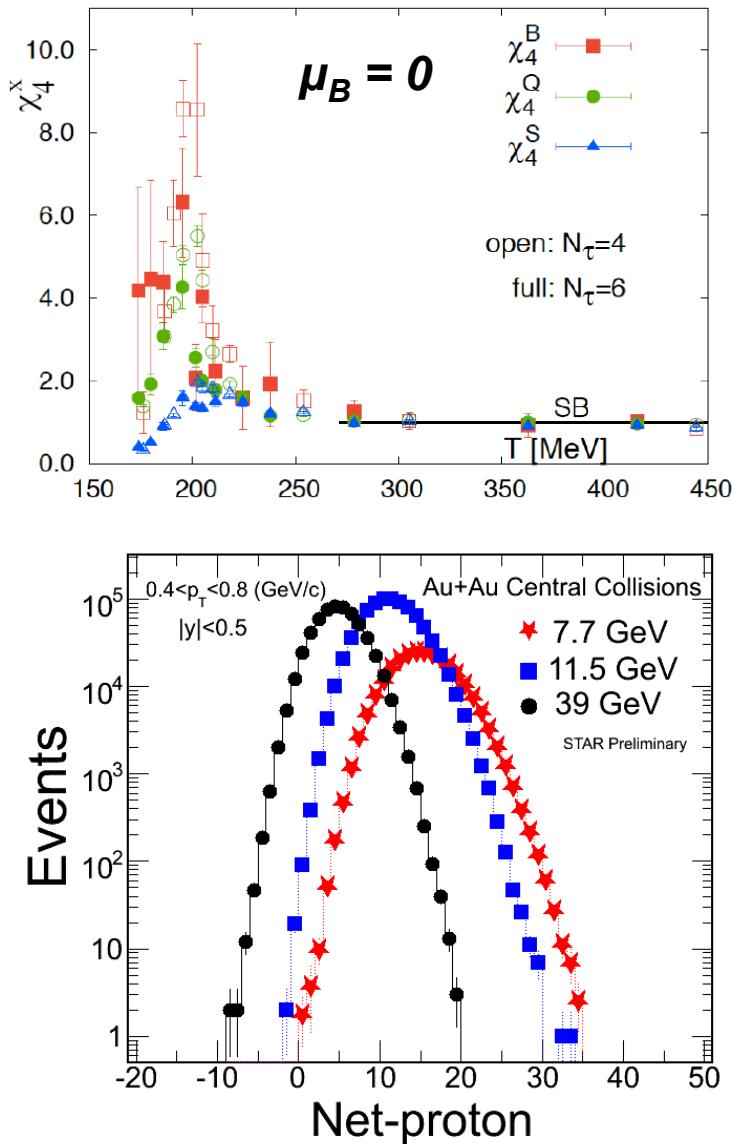


(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PRC86, 44902(13)]

(b) NJL model: Hadron splitting consistent. Sensitive to vector-coupling, **CME**,  $\mu_B$  driven. [J. Xu, et al., PRL112.012301(14)]

(c) Pure Hydro solution with  $\mu_B$ , viscosity: **Chemical potential  $\mu_B$  and viscosity  $\eta/s$  driven!** [Hatta et al. arXiv:1502.05894//1505.04226//1507.04690 ]

# Higher Moments



1) Higher moments of conserved quantum numbers:  **$Q$ ,  $S$ ,  $B$** , in high-energy nuclear collisions

2) Sensitive to critical point ( $\xi$  correlation length):

$$\langle (\delta N)^2 \rangle \approx \xi^2, \quad \langle (\delta N)^3 \rangle \approx \xi^{4.5}, \quad \langle (\delta N)^4 \rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \quad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

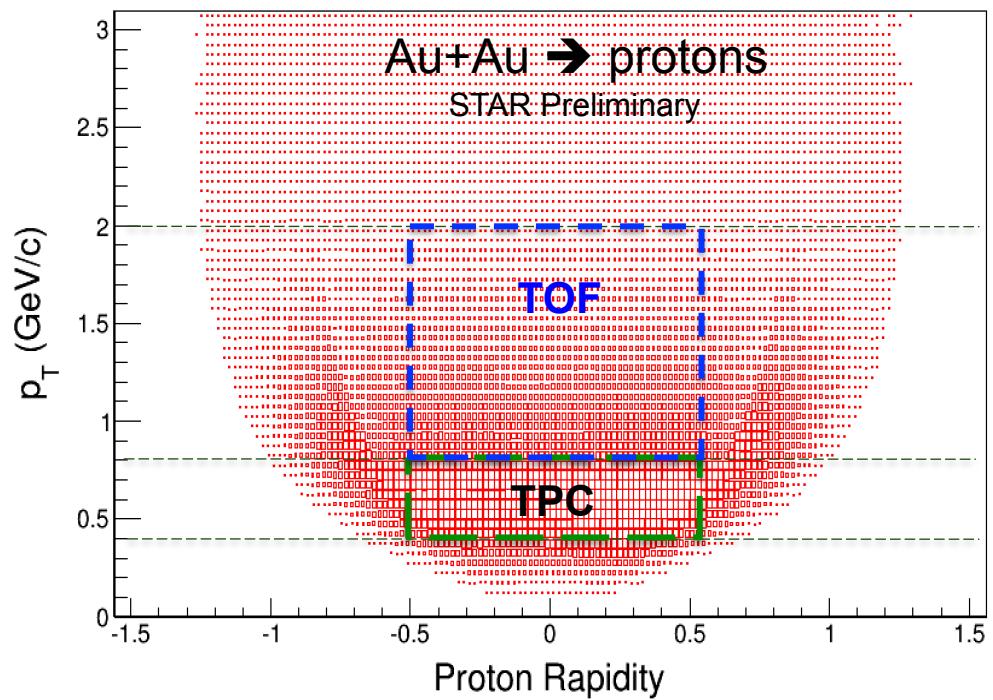
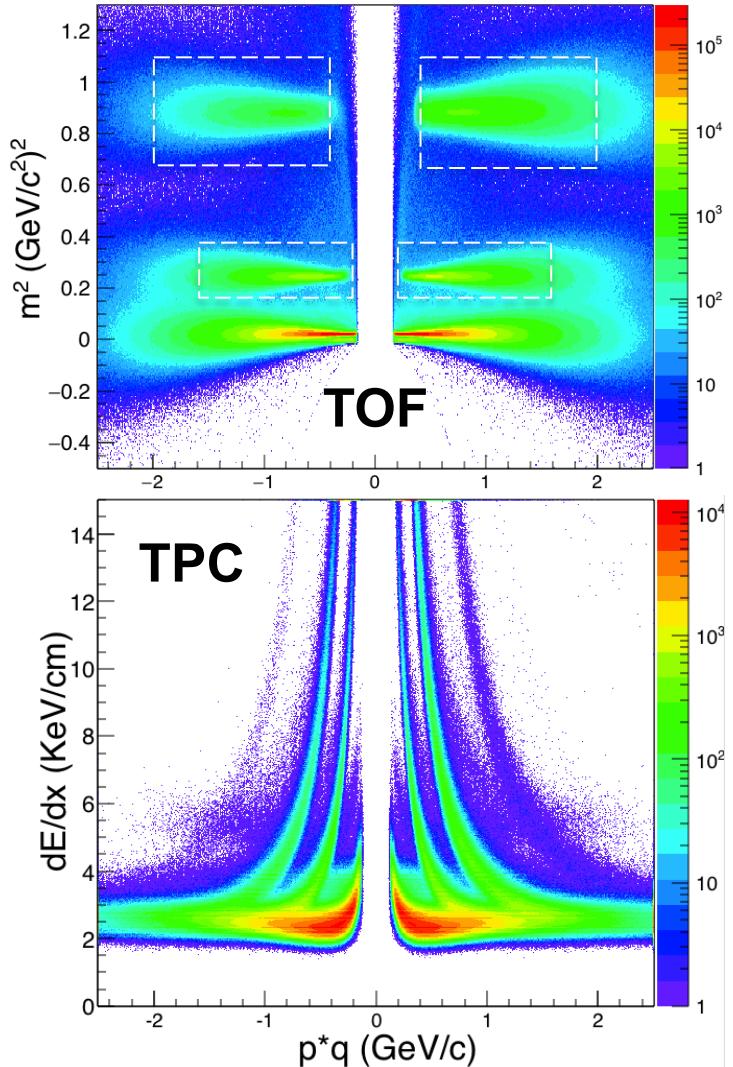
4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

## References:

- STAR: *PRL*105, 22303(10); *ibid*, 032302(14)
- M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB*696, 459(11) // F. Karsch et al, *PLB*695, 136(11) // S.Ejiri et al, *PLB*633, 275(06)
- A. Bazavov et al., *PRL*109, 192302(12) // S. Borsanyi et al., *PRL*111, 062005(13) // V. Skokov et al., *PRC*88, 034901(13)

# Proton Identification with TOF

**Published net-proton results:** Only TPC used for proton/anti-proton PID.  
TOF PID extends the phase space coverage.



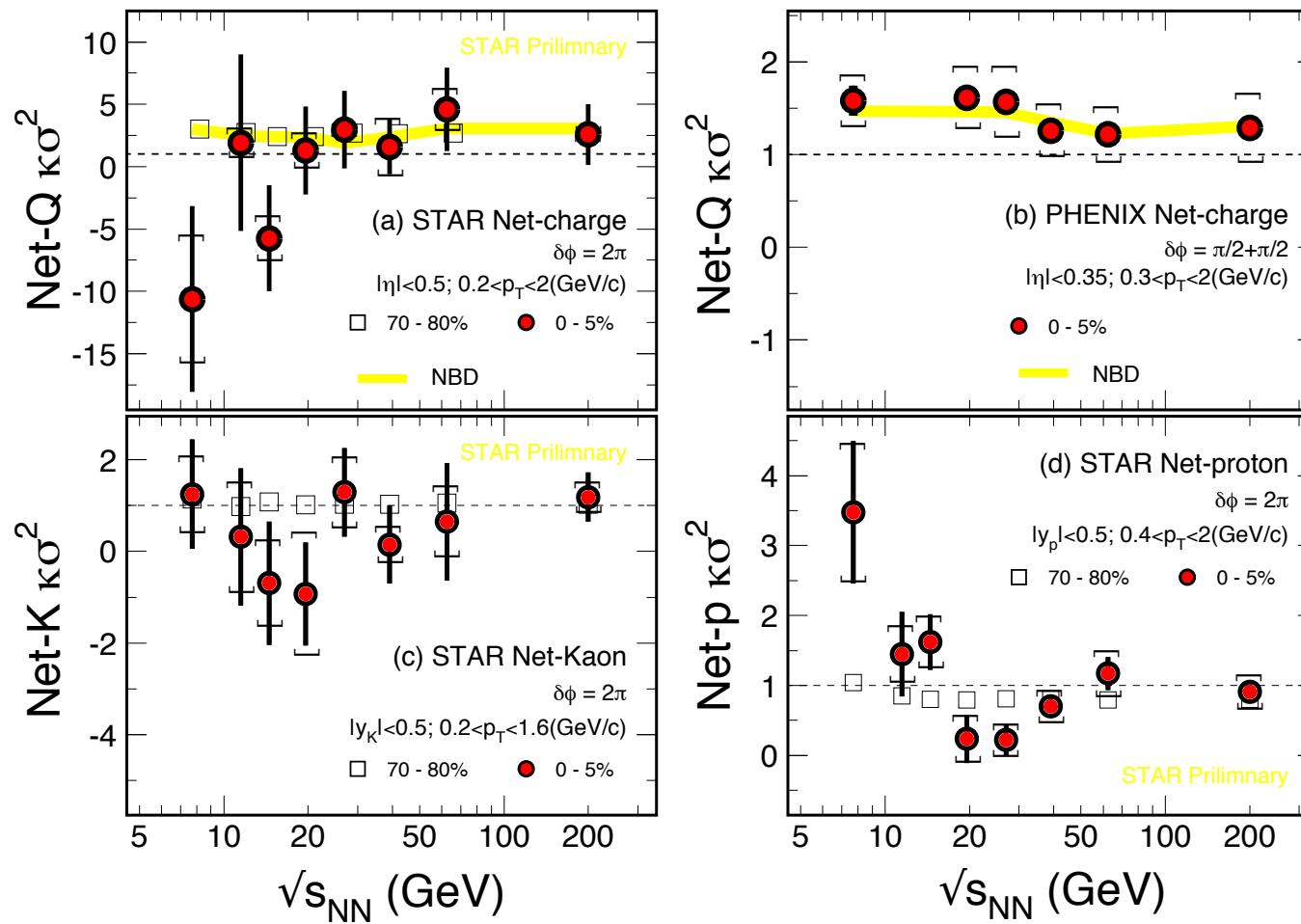
**Acceptance:**  $|y| \leq 0.5, 0.4 \leq p_T \leq 2 \text{ GeV}/c$

**Efficiency corrections:**

TPC ( $0.4 \leq p_T \leq 0.8 \text{ GeV}/c$ ):  $\epsilon_{\text{TPC}} \sim 0.8$

TPC+TOF ( $0.8 \leq p_T \leq 2 \text{ GeV}/c$ ):  $\epsilon_{\text{TPC}} * \epsilon_{\text{TOF}} \sim 0.5$

# Higher Moment of Net -Q, -K, -p



$$error(K * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

In STAR:

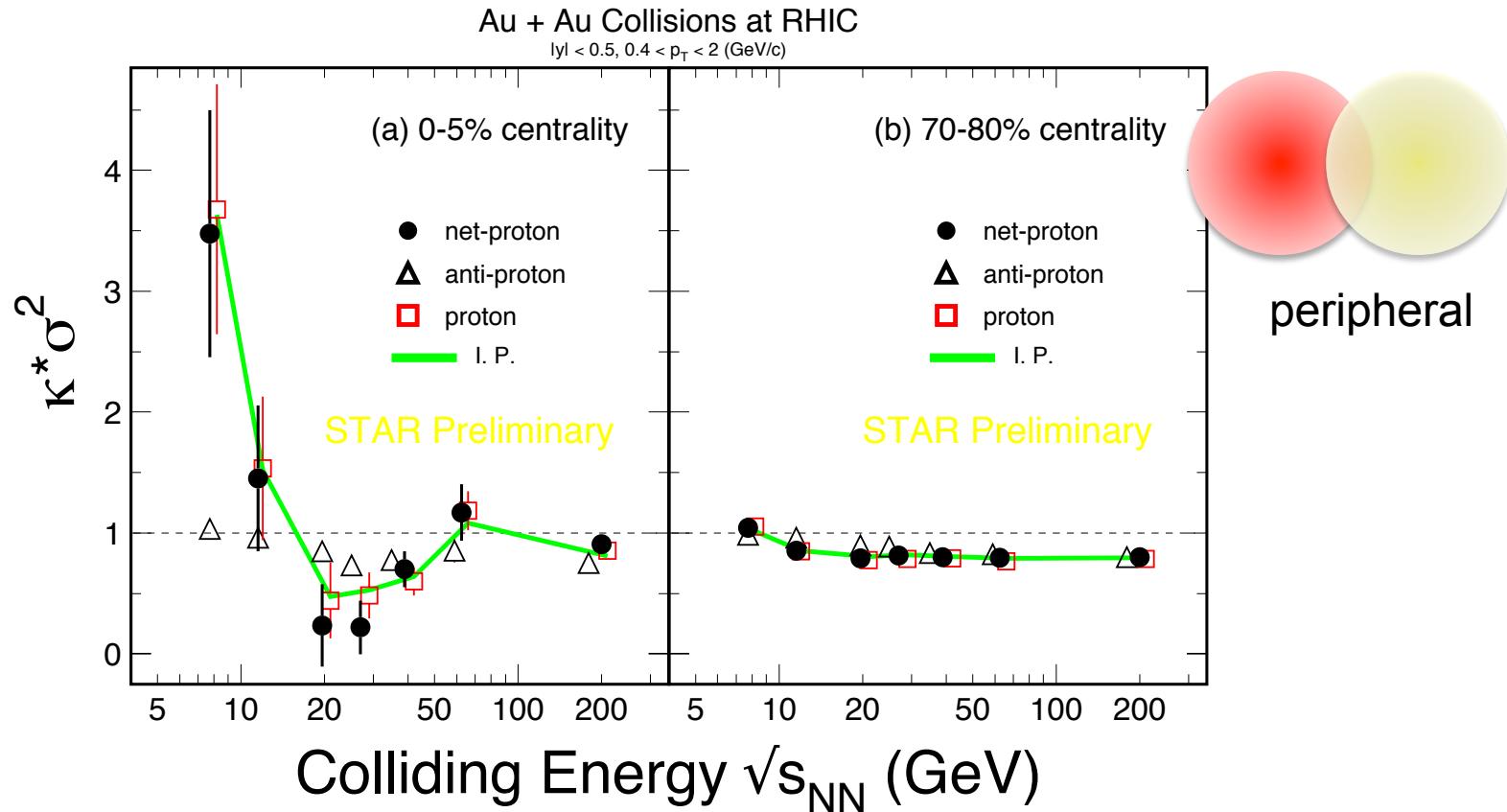
$$\sigma(Q) > \sigma(K) > \sigma(p)$$

- 1) Higher moment of net-Q, net-Kaon, and net-proton measured at RHIC BES-I
- 2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions at  $\sqrt{s_{NN}} < 27 \text{ GeV}$ !

PHENIX: talk by P. Garg at QM2015; STAR: talk by J. Thäder and poster by J. Xu at QM2015



# Net-proton Higher Moment



**Net-proton results:** All data show deviations below Poisson for  $\kappa\sigma^2$  at all energies. Larger deviation at  $\sqrt{s_{NN}} \sim 20$  GeV.

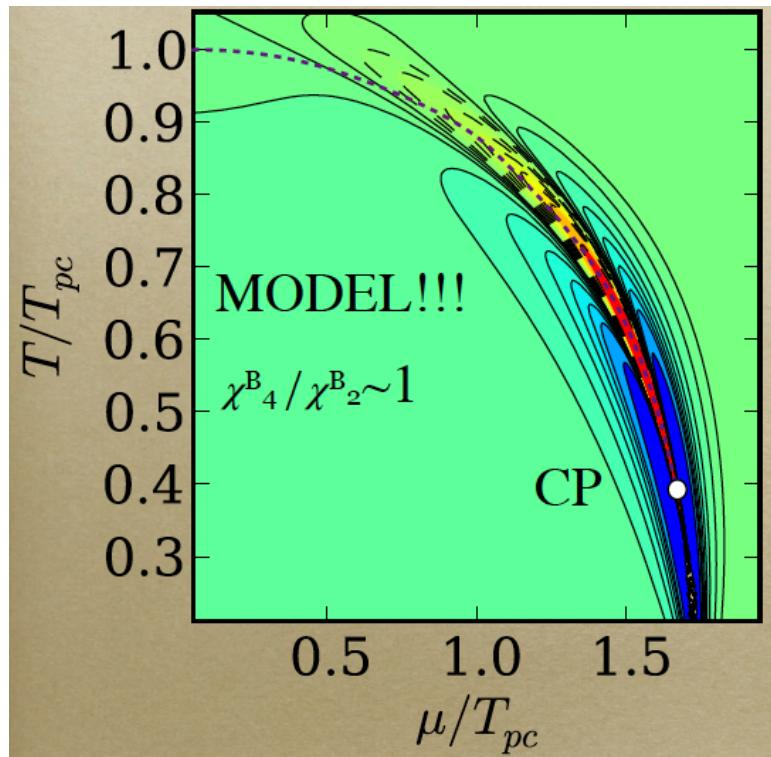
## Non-monotonic behavior in central collision!

X.F. Luo, CPOD2014, QM2015

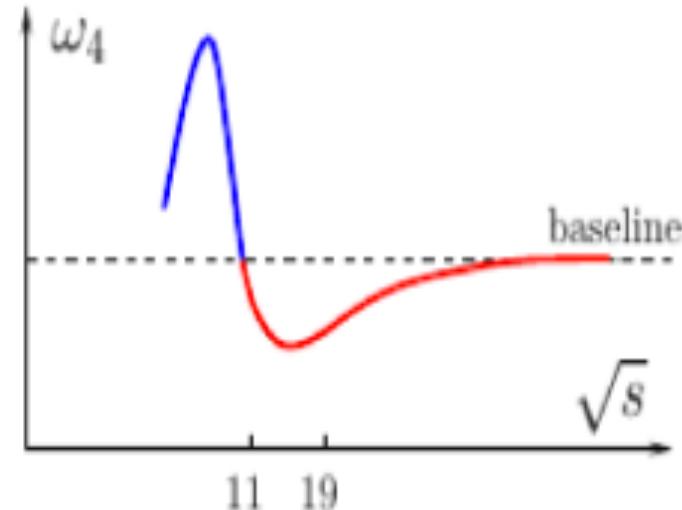
**Question:** What will happen at even lower collision energy?

# Expectation from Calculations

V. Skokov, Quark Matter 2012

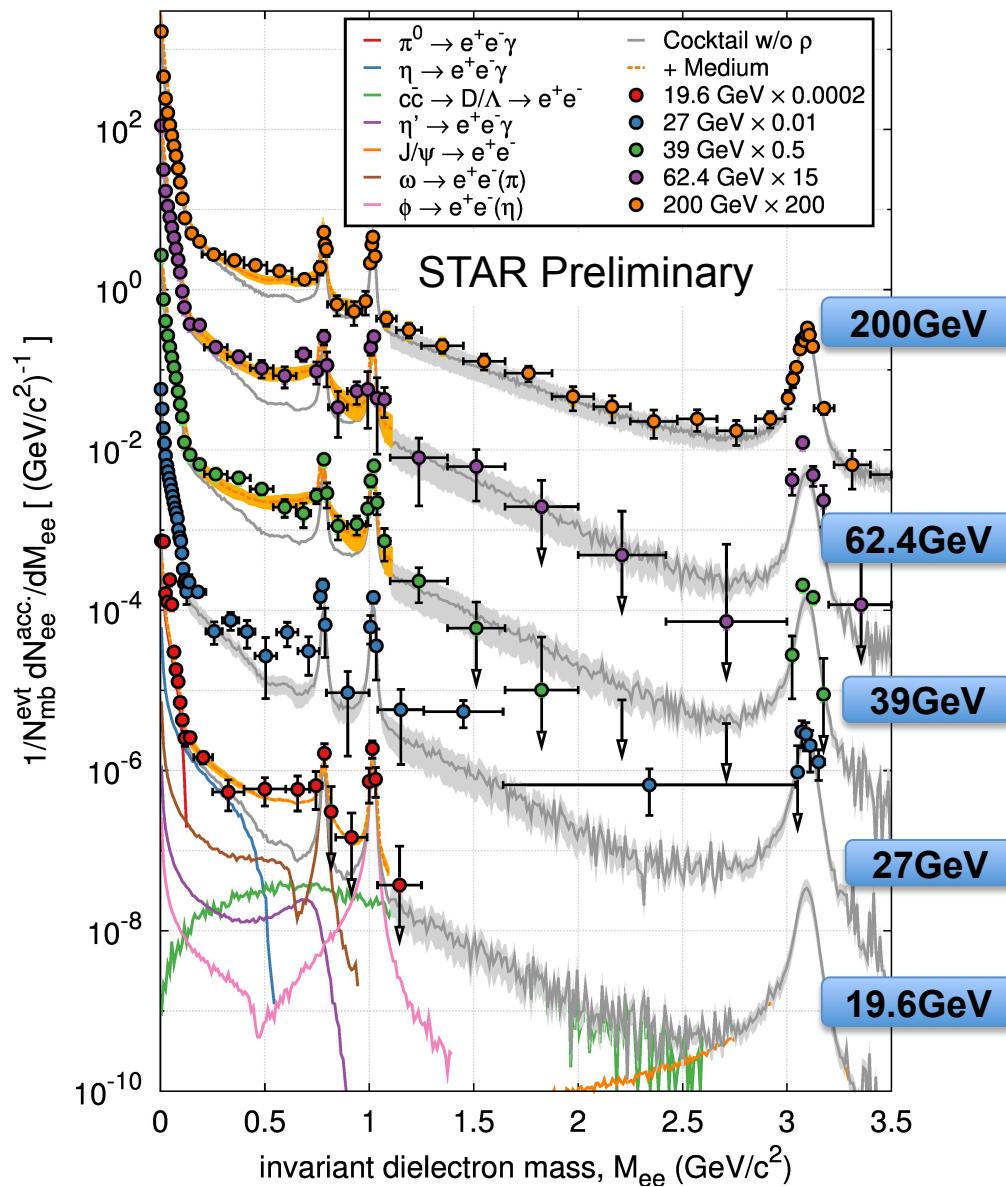


M. Stephanov, *PRL*107, 052301(2011)



Characteristic “Oscillating pattern” is expected for CP.

# Energy Dependence of Di-electrons

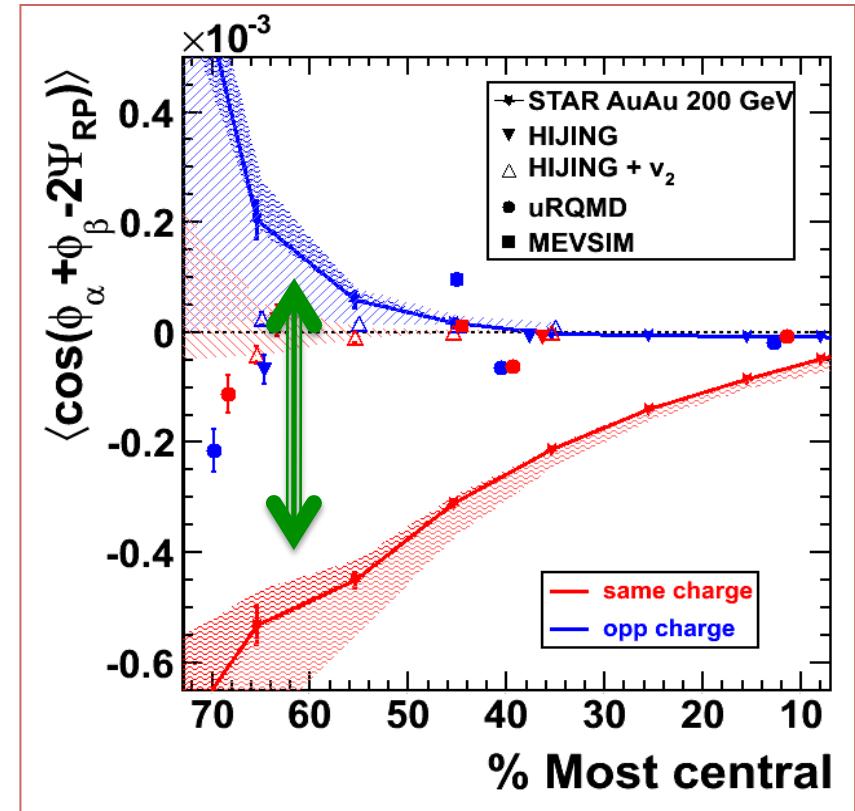
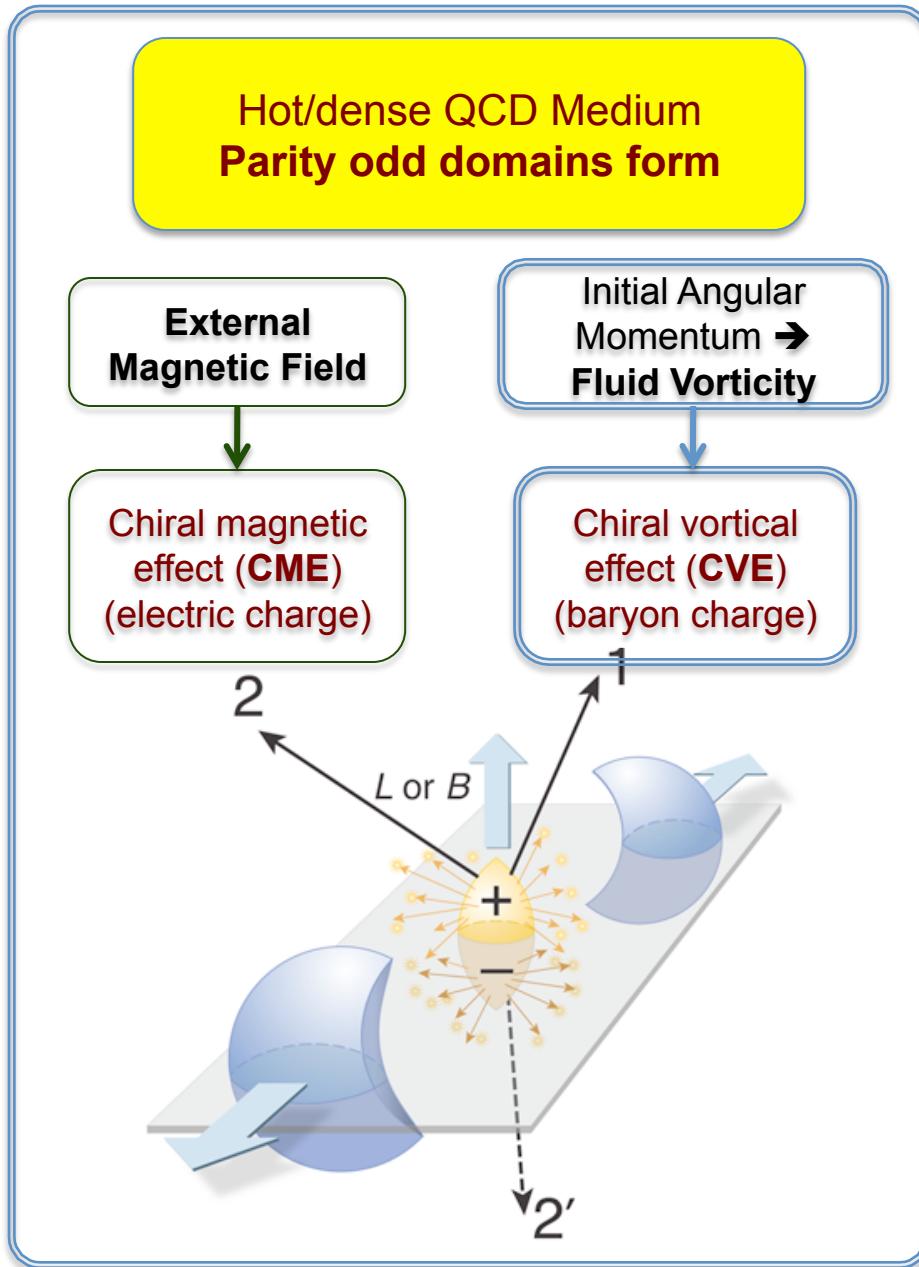


## Bulk-penetrating probe:

- 1)  $M_{ee} \leq 1 \text{ GeV}/c^2$ : In-medium broadened  $\rho$ , model results\* are consistent with exp. data. (\* driven by the baryon density in the medium)
- 2)  $1 \leq M_{ee} \leq 3 \text{ GeV}/c^2$ : Thermal radiation:  $\exp(-M_{ee}/T)$ ? HFT: Charm contributions.
- 3) High statistics data are needed, **BES-III!**

- STAR: PRL113, 22301(14); arXiv:1312.7397  
- R. Rapp: PoS CPOD13, 008(2013)  
- O. Linnyk et al, PRC85, 024910(12)

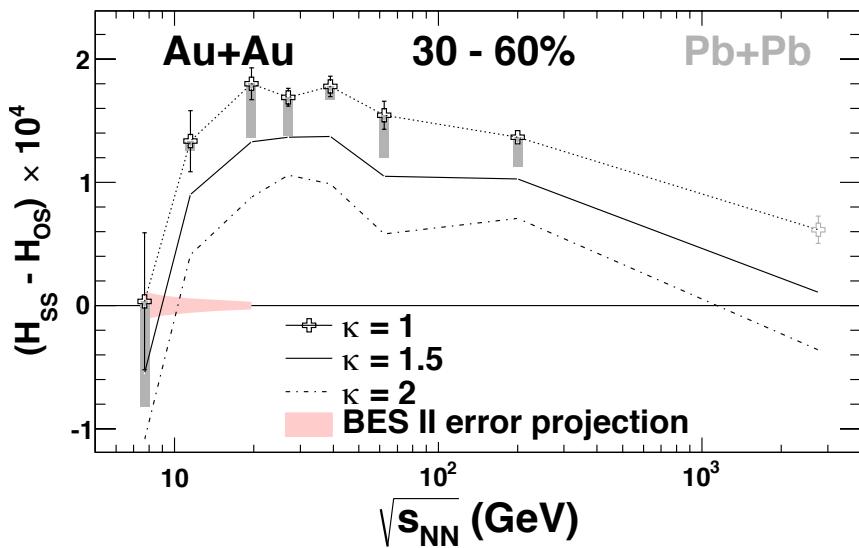
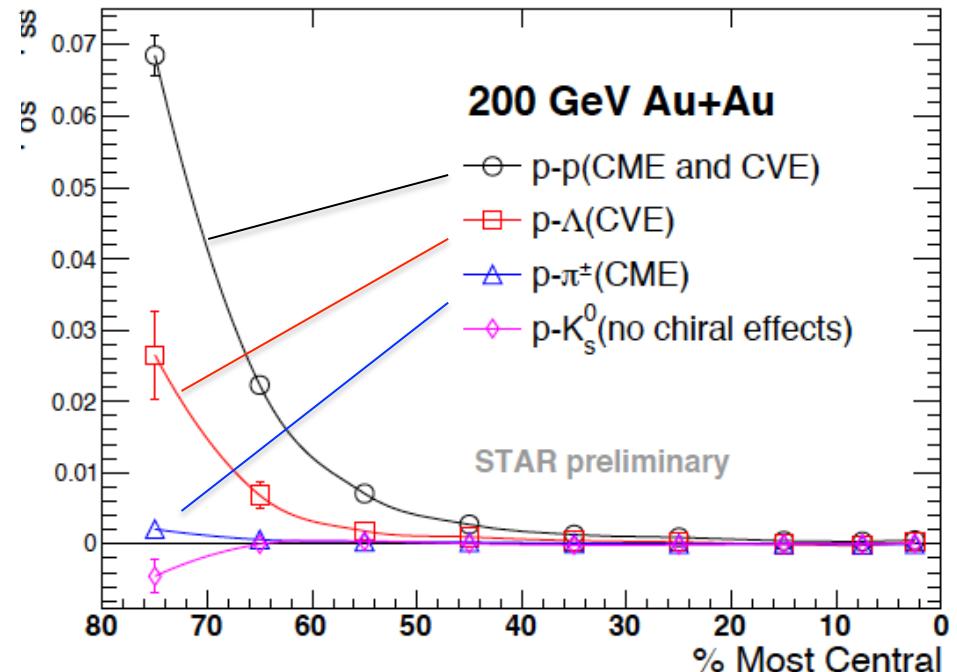
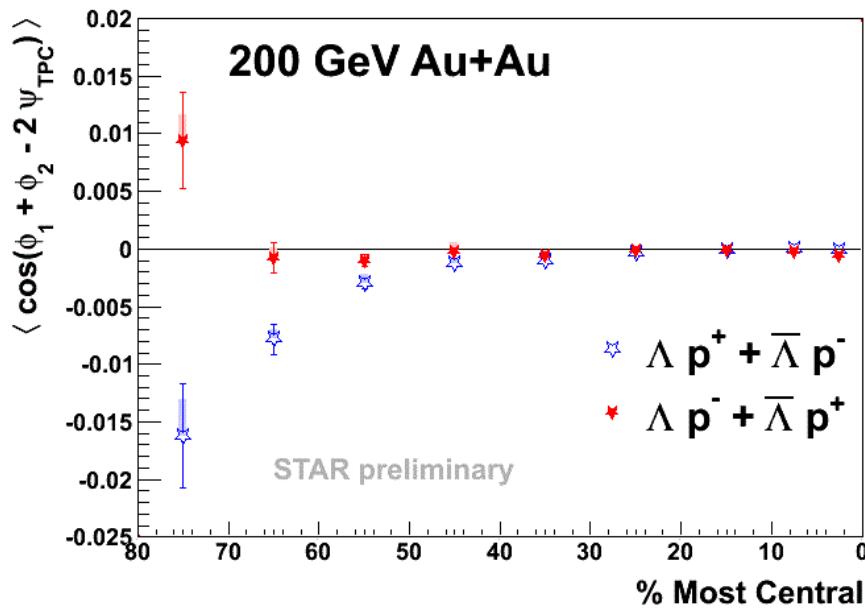
# Study Chiral Effects (Global)



Charge pair correlation results are consistent with CME effect in non-central Au+Au collisions

- STAR: F. Zhao, NPA931, c746(14)  
PRL. 103, 251601(09) ; 113, 52302(14)  
D. Kharzeev, D.T. Son, PRL106, 062301(11)  
D. Kharzeev. PLB633, 260 (06)  
D. Kharzeev, et al. NPA803, 227(08)

# Charge Separation wrt Event Plane



- 1) CVE
- 2) Global Chiral effect hierarchy:
- 3) LPV(CME) disappears at low energy:  
→ hadronic interactions become dominant at  $\sqrt{s_{NN}} \leq 11.5$  GeV

STAR: PRL. 103, 251601(09); 113, 52302(14)  
 Q.Y. Shou, NPA931, c758(14); F. Zhao, NPA931, c746(14)  
 L.W. Wen, poster at QM2015  
 D. Kharzeev, PLB633, 260 (06)  
 D. Kharzeev, et al. NPA803, 227(08)

# The BES-II Program at RHIC



# BES II Related Upgrades



## 1) RHIC Electron Cooling:

- Luminosity increase by factors of 3-10 for  $5 < \sqrt{s}_{NN} < 20$  GeV

## 2) Inner TPC (iTPC):

- Extends rapidity coverage:  $|y_p|$  from 0.5 to 0.8 →  
**Crucial for QCD CP study**
- Improved tracking efficiency and  $dE/dx$  →  
**Important for di-electron measurements**

## 3) Event Plane Detector (EPD):

- Extends pseudo-rapidity coverage to:  $1.8 < |\eta| < 4.5$  →  
**Trigger and event selection: multiplicity, event-plane**

## 4) End Cap TOF (eTOF) – (CBM-STAR):

- Extends PID to about  $|\eta| < 1.5$  →  
**Fixed-target program  $\mu_B \Rightarrow 700$  MeV**



# STAR Detector System



EEMC

Magnet

MTD

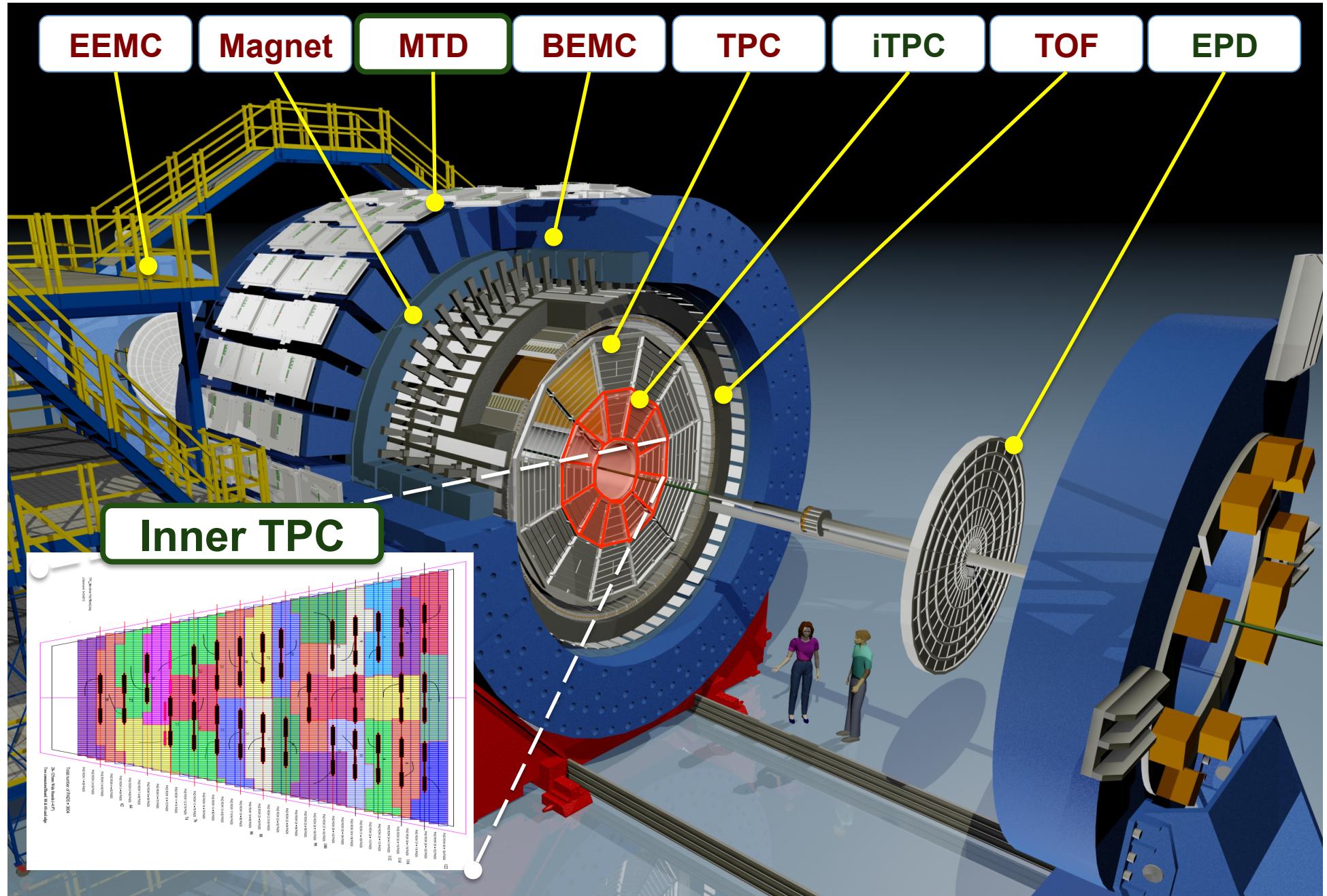
BEMC

TPC

iTPC

TOF

EPD





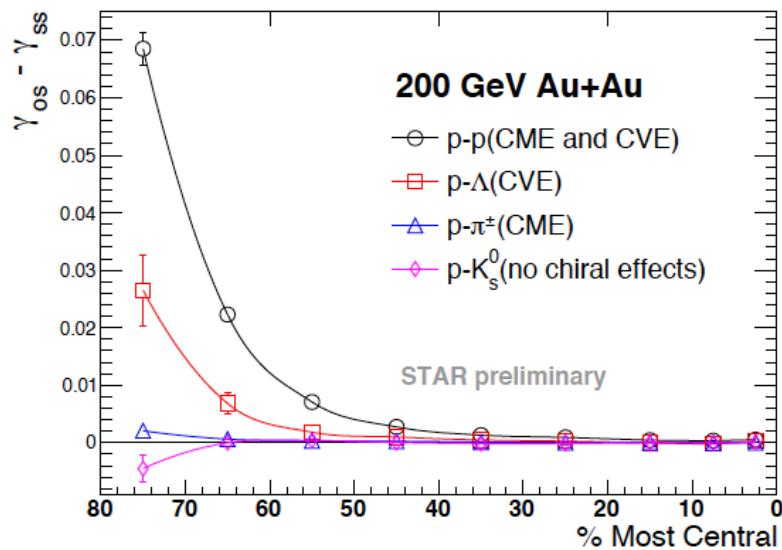
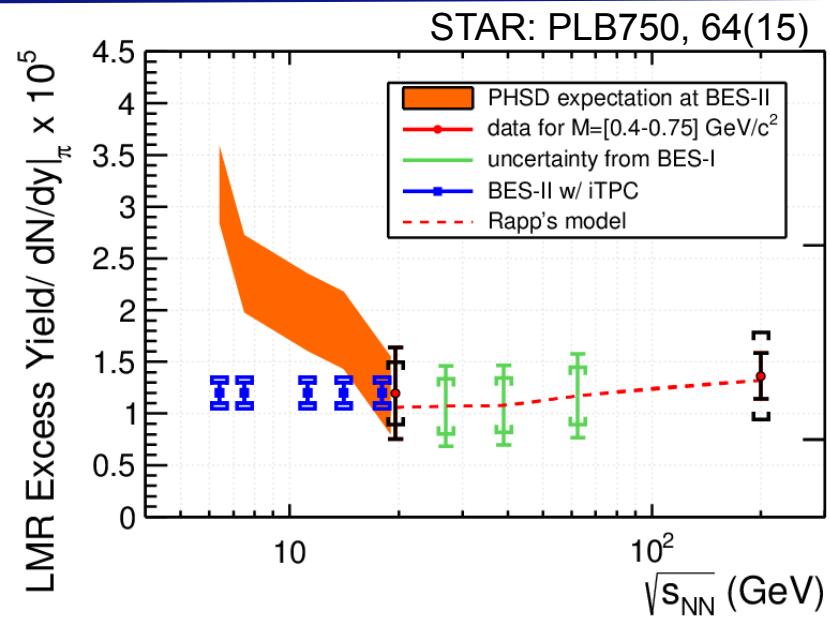
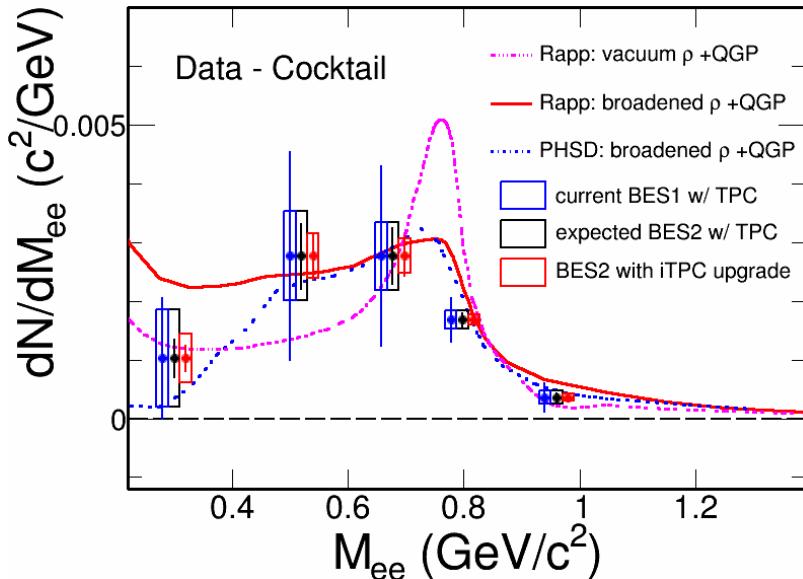
# Event Statistics for BES II at RHIC



$\sqrt{s}_{NN}$ (GeV)	Events ( $10^6$ )	BES II / BES I	Weeks	$\mu_B$ (MeV)	$T_{CH}$ (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
39	39	2010		112	164
27	70	2011		156	162
19.6	<b>400</b> / 36	<b>2019-20</b> / 2011	<b>3</b>	206	160
14.5	<b>300</b> / 20	<b>2019-20</b> / 2014	<b>2.5</b>	264	156
11.5	<b>230</b> / 12	<b>2019-20</b> / 2010	<b>5</b>	315	152
9.2	<b>160</b> / 0.3	<b>2019-20</b> / 2008	<b>9.5</b>	355	140
7.7	<b>100</b> / 4	<b>2019-20</b> / 2010	<b>14</b>	420	140

1) Event statistics driven by QCD CP search and di-electron measurements

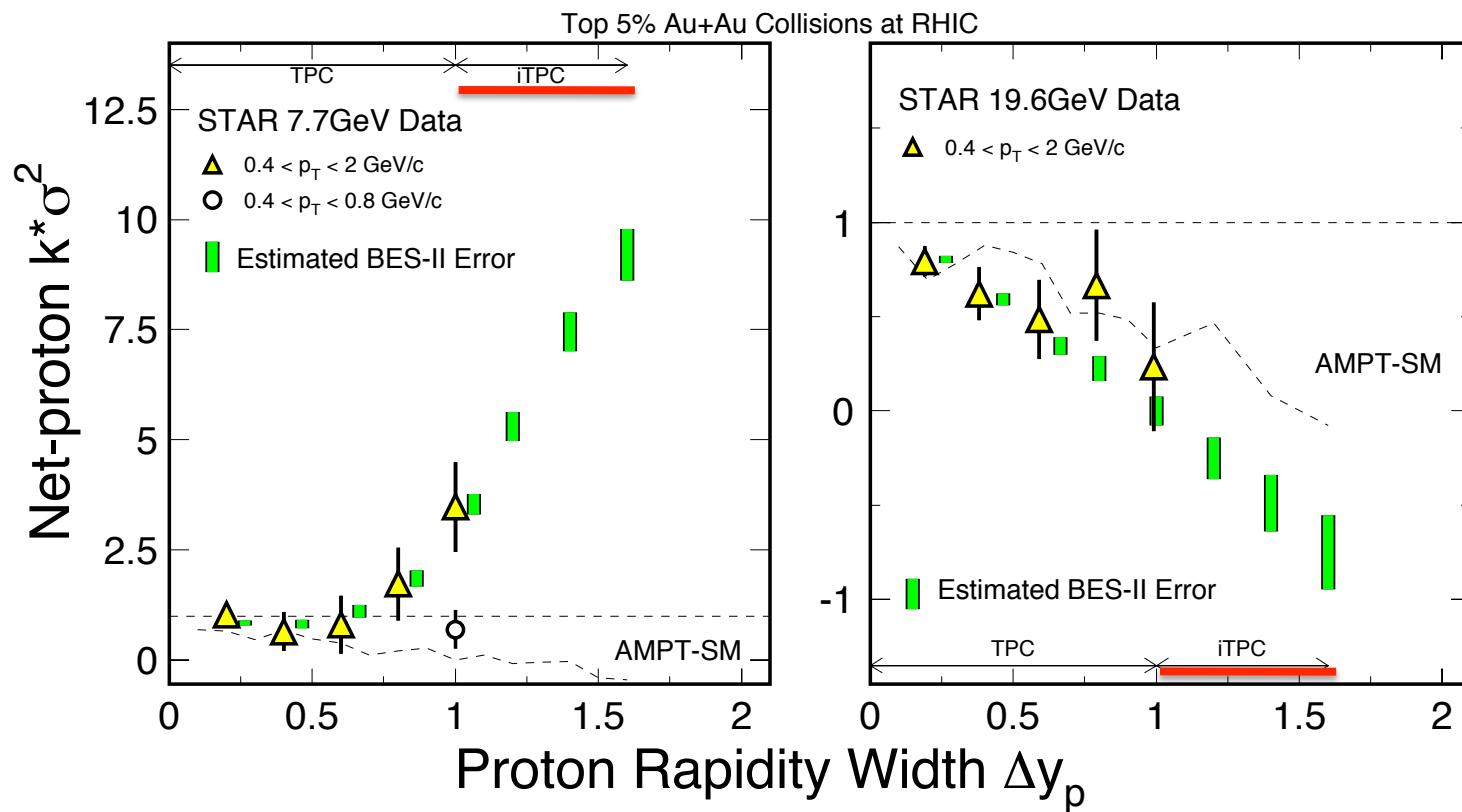
# BES-II: Chiral Properties



## High net-baryon region:

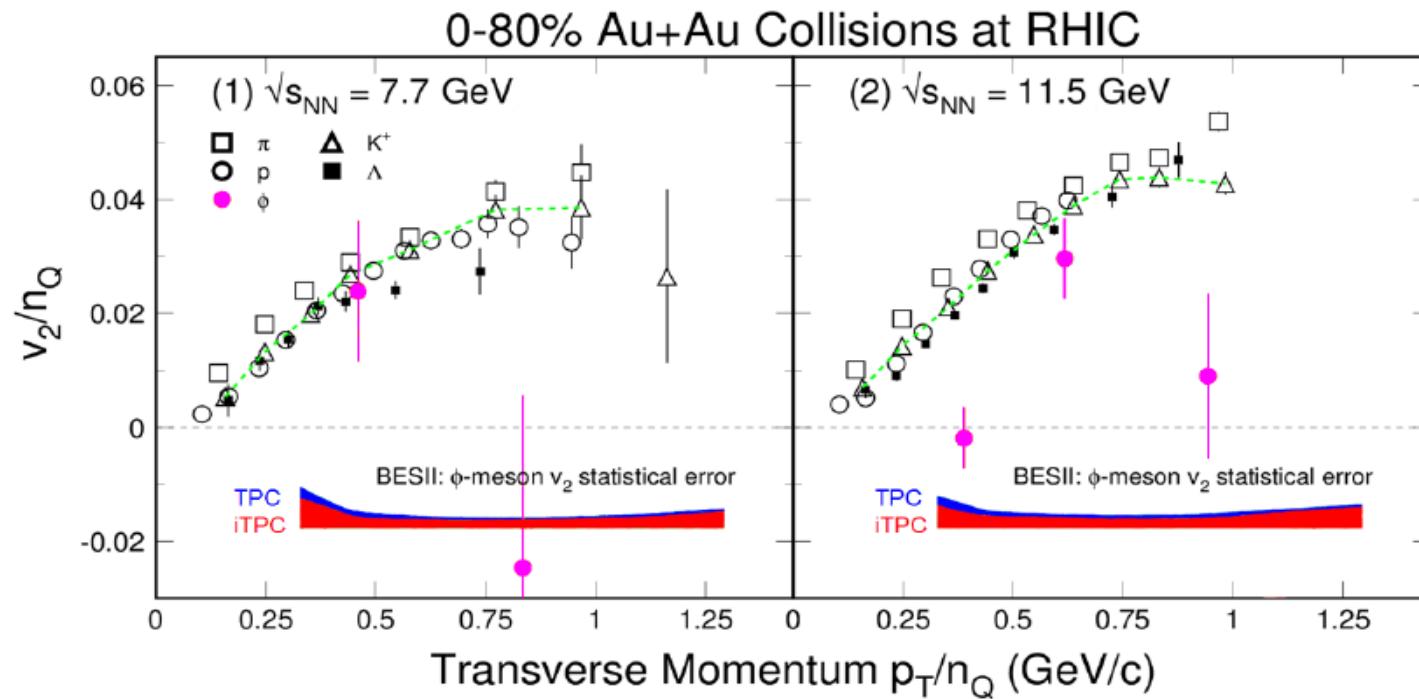
- 1) Precision measurements on di-electron distributions
- 2) Global Chiral properties with identified hadrons

# BES-II: Critical Point



- 1) iTPC extend the rapidity coverage to  $\Delta y = 1.6$ , allowing to studying kinematic acceptance for the CP (CR) search
- 2) Precision measurement of net-proton higher moments at high net-baryon region

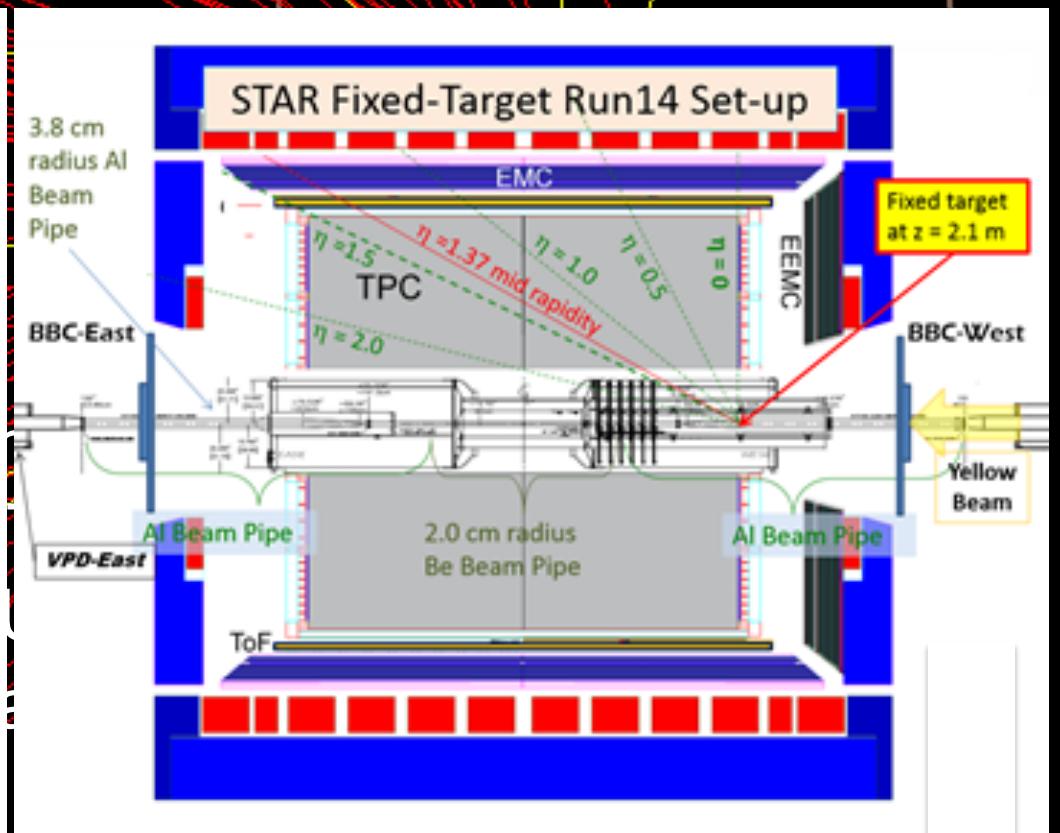
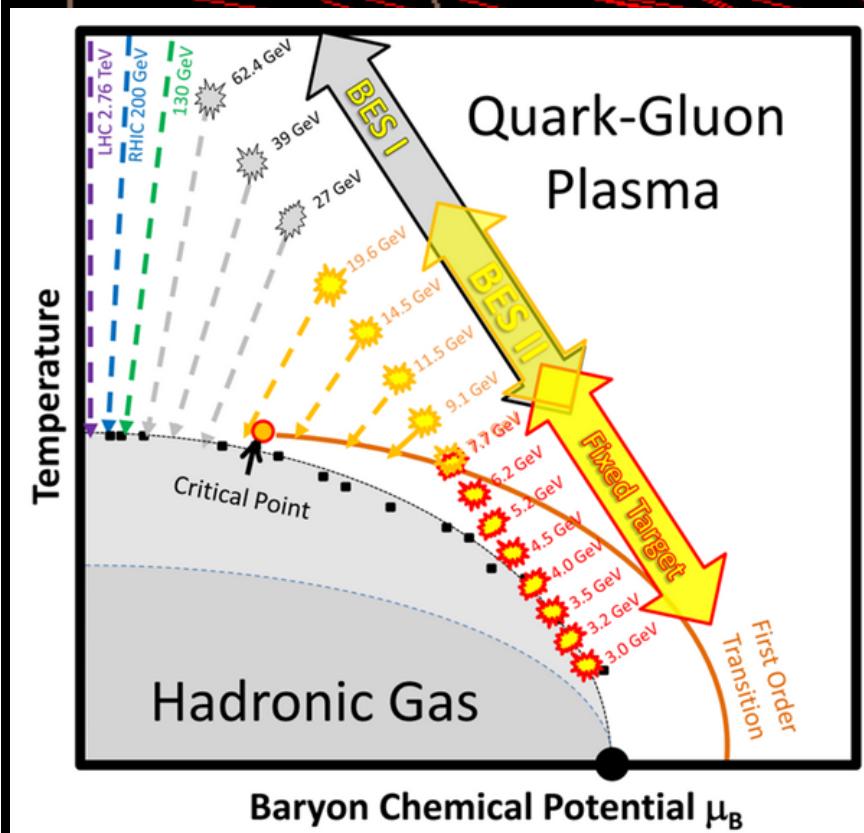
# BES-II: Collectivity



- 1) Precision measurement for  $\phi$ -meson  $v_2$ .
- 2) Study the partonic vs. hadronic interactions in the high net-baron region.

**UCDAVIS**

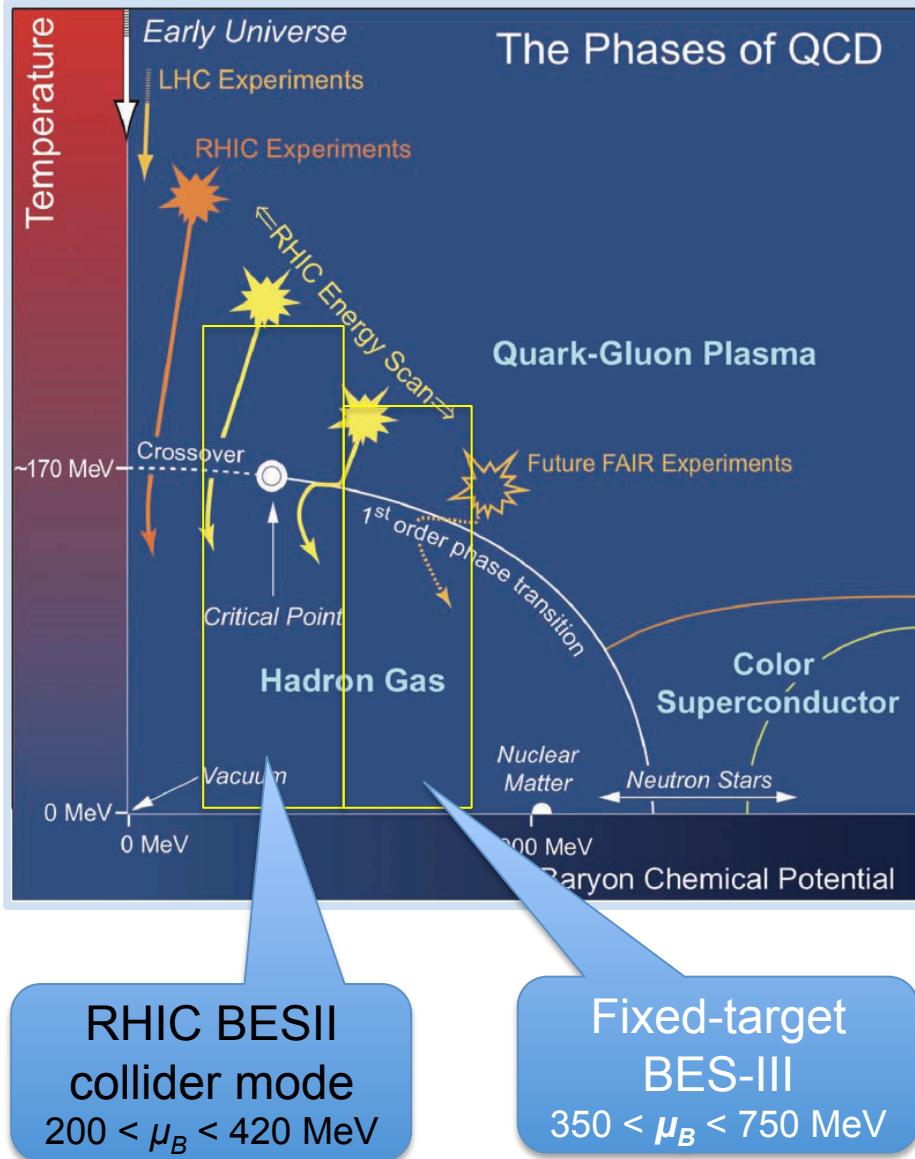
# Results from Fixed Target Collisions at STAR



Kathryn Meehan



# Summary



RHIC e-cooling and iTPC upgrades bring BES-II a **new era** for studying the QCD phase structure at high net-baryon region ( $200 < \mu_B < 420$  MeV) with unprecedented precision and coverage. Possible new discoveries are:

- 1) The QCD critical point (region) and phase boundary
- 2) Properties with Chiral symmetry

**Longer Future:** fixed-target experiment at extreme large net-baryon density,  $350 < \mu_B < 750$  MeV ( $8 < \sqrt{s_{NN}} < 2$  GeV)